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<p>Pictures help people to comprehend and remember texts. The goal of this project is to begin to understand how this occurs. This Final Technical Report describes progress in three areas. First, we have demonstrated that pictures are used to modify the mental representation derived from texts. When reading with pictures, people tend to form mental models, even when reading in relatively unfamiliar domains. These mental models are representations of what the text is about (in contrast to representations of the text itself), they have an analogical character, and they are constructed using the visual/spatial sketchpad of working memory. Second, we have documented some comprehension processes that are affected by pictures and some that are not. In particular, ease of anaphor resolution is independent of the presence or absence of pictures. On the other hand, pictures enhance the reader's ability to compute a particular kind of elaborative inference that we call noticing. These inferences are derived from spatial relations within the mental model, but need not represent spatial information. Third, we describe a computer simulation that demonstrates how the various processes and representations identified experimentally can be coordinated using a limited-capacity system.</p>			
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A. List of Objectives

Leafing through textbooks, manuals, and newspapers will quickly demonstrate that pictorial information is common in non-narrative texts. The belief shared by authors and readers is that the pictorial information assists comprehension and memory for the information. In fact, the vast majority of the experimental literature investigating the effects of pictures on comprehension corroborates this belief. Nonetheless, there is little in that literature to suggest how it is that pictures produce this benefit. The intent of the research described in this report is to discover the cognitive mechanisms underlying the beneficial effects of pictures in text. The strategy will be to work on two closely related objectives. Objective 1: Identify how pictures (diagrams) modify the representation of information gained from text. Objective 2: Identify how pictures (diagrams) modify the processing of textual information.

Investigation of these objectives will proceed by contrasting two theoretical views. The first is Paivio's (1986) dual-coding theory which proposes that pictorial and verbal information are represented as separate codes. According to this view, pictures help comprehension by ensuring the existence of an additional code which may be used to assist remembering. The second view is derived from the mental model interpretation of text comprehension. According to this view, the goal of comprehension processes is to represent the objects and events described by the text, rather than a representation of the text itself (Garnham, 1987; Glenberg, Meyer, & Lindem, 1987). This view proposes that the mental model integrates pictorial and verbal information in a single code (although separate pictorial and verbal codes may also be generated). Pictures help comprehension by assisting construction of a mental model (that is, an integrated representation of the referent situation described by the text) which more closely captures the referent situation than a representation derived from the text alone.

B. Status of the research effort.

We have made substantial progress on identifying how pictures affect the representation of information gleaned from texts. In overview, a primary effect is that pictures help people to build mental models of the text. A secondary effect is that pictures also seem to provide a long-term imaginal code that can benefit performance on comprehension tests.

As a cognitive representation of a text, a mental model is a representation of what a text is about, not a representation of the linguistic entities and structure of the text itself. Although there are several representational formats that are consistent with this definition (e.g., Johnson-Laird, 1983; Van Dijk and Kintsch, 1983; Just and Carpenter, 1991), we believe that such models are often based on dimensions of experience. In particular, it appears that mental models are often spatial, making use of our abilities to represent spatial relations and manipulate cognitive entities within such a representation. Thus, when reading a description of the Taj Mahal (or of a non-existent object such as the colossus of Ozymandius) we are able to develop a representation of what the object looks like (including its spatial extent), not just a representation of the words and sentences used to describe the object. Spatial representations may also be used to represent non-spatial information. Thus, the order of steps in a procedure may be represented as a spatially arrayed flowchart, or the energy levels of subatomic particles may be represented (cognitively) as locations along a horizontal dimension representing amount of energy.

In what sense do mental models capture the idea of comprehension? One function of language is to inform us about objects and events that are not perceptually available. If language is to be of use in this regard, it must direct us to represent the new information in a useful format. That is, the format should facilitate recognition and manipulation of the objects. Because most objects have a spatial extent, comprehension of text virtually requires a spatial, model-like representation if the text is to be useful. Glenberg, Kruley, and Langston (in press) give details regarding such a representation.

How do pictures help comprehension? Data reported in Glenberg and Langston (1992) are the primary evidence for our claim that pictures help people to build mental models. In those experiments, students read brief descriptions of four-step procedures (e.g., how to write a term paper). In the critical texts, the text explicitly

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stated that the first step was followed by steps two and three which were performed simultaneously, and then the fourth step. Although steps 2 and 3 are performed simultaneously, by necessity, they are described one after the other. Half of the subjects read the texts alone, and half read the texts accompanied by a flowchart that illustrated the order of the four steps. Following the reading of each text, we assessed the strength of the relationship between steps that were described near each other in the text (e.g., steps 1 and 2 or steps 3 and 4) or steps that were described far from each other in the text (e.g., steps 1 and 3 or steps 2 and 4). Note however, that for all of these pairs, the steps within a pair occur immediately after one another when the procedure is executed. Thus, if subjects are representing the order of the steps in the procedure (a mental model of the procedure) the relation between steps in a far pair should be just as strong as the relation between steps in a near pair; in the *procedure*, steps in these pairs are adjacent. However, if subjects are representing the order of the steps in the text, the relation between steps in a far pair should be weaker than the relation between steps in a near pair.

The data were very clear. When the texts were accompanied by a picture, the subjects formed a mental model (representation of the order of the steps in the procedure), whereas when the texts were read alone, the subjects formed a representation of the text. Various control conditions allowed us to eliminate alternative explanations based on dual-code theory, motivational factors associated with pictures, and selective repetition of information presented in pictures. In addition, we were able to demonstrate that when the pictures depicted the order in which the steps were described in the text (thus the pictures reinforced the text, but not the procedure itself), comprehension suffered compared to having no pictures at all.

These results are significant for several reasons. First, they are among the first to demonstrate how it is that pictures facilitate comprehension. At the risk of redundancy: Pictures help readers to construct mental models. Second, they are the first to demonstrate construction of a spatial mental model for texts that describe non-spatial domains (e.g., the temporal order of steps in a procedure).

The mental models account has not gone unchallenged. McKoon and Ratcliff (1992) have offered a new account of data that had heretofore been regarded as among the strongest demonstrating mental models. I will describe that original data (Glenberg, Meyer, and Lindem, 1987) first, then the McKoon and Ratcliff alternative, and finally, our response (Glenberg and Mathew, 1992). In the Glenberg et al. (1987) experiments, subjects read brief descriptions that included one of two versions of a critical sentence. In the associated version, the critical sentence associated a main actor (e.g., John) and a target object (e.g. sweatshirt). An example is, "After warming up, John put on his sweatshirt and jogged halfway around the lake." In the dissociated version, the critical sentence dissociated the main actor and the target object, as in "After warming up, John took off his sweatshirt and jogged halfway around the lake." Following the critical sentence, the main actor was kept foregrounded by pronominal reference, whereas the target was never again mentioned or referred to. Availability of the target object was tracked by how quickly subjects could recognize the target object (sweatshirt) when presentation of the word naming the target interrupted reading. If subjects were representing the text, then responding to the target should be equally fast in the associated and dissociated conditions: in both conditions the target object is mentioned once in relation to the main actor. If subjects were representing a mental model of what the text is about, the prediction is quite different. In the mental model formed in the associated condition, the main actor and the target object are spatially related. Hence when the main actor is foregrounded, it is likely that the target is too. In the mental model formed in the dissociated condition, the main actor and the target object are spatially dissociated. Hence when the main actor is foregrounded, it is less likely that the target object is foregrounded. Thus, the prediction based on the mental model account is faster responding to the target in the associated condition than in the dissociated condition. This is just what Glenberg et al. (1987) found.

McKoon and Ratcliff (1992) suggested an alternative account of these data based on the notion of salience. The idea is that by virtue of association with the main character, salience is conferred on the target item (and the propositions derived from the sentence). According to this alternative, the faster responding in the associated condition does not reflect construction of a spatial mental model, instead it reflects salience or enhanced accessibility conferred by association. To test this idea, McKoon and Ratcliff added to the texts a location for the critical target item. Thus, John might be described as putting on a sweatshirt from the laundry (the location). Because the location is part of the associated (or dissociated) context, salience is also conferred on the location, and hence it should be responded to more quickly in the associated condition relative to the dissociated condition. The prediction from the mental model account is different. Because (according to McKoon and Ratcliff) the

location is always spatially distant from the main actor, responding to the location should not vary as a function of the associated/dissociated status of the target object (sweatshirt). In fact, McKoon and Ratcliff found that both the target object and its initial location were affected by the associated/dissociated variable, as predicted from the salience account.

Glenberg and Mathew (1992) discussed several logical problems with the salience account. They also reported two experimental tests of the account. First, they asked subjects to rate the salience (defined as importance in the text) of both the critical object and the initial location in the associated and dissociated versions of the texts. The salience account predicts higher ratings of both the object and the location in the associated condition compared to the dissociated condition. For the object, rated salience increased some (but not a statistically significant amount) from the dissociated to the associated condition. For the location, rated salience decreased substantially from the dissociated to the associated condition, just the opposite of the prediction from the salience account.

If salience does not control responding in this task, what produced McKoon and Ratcliff's original finding? In preparing the texts for the rated salience experiment, we discovered that about 25% of McKoon and Ratcliff's texts did not clearly meet their stated condition that the initial location and the main actor were always spatially dissociated. For example, in one text, the main actor is a fisherman, the object is a bag of chips that blows into the boat (associated) or into the water (dissociated) and the initial location of the chips is the fisherman's hand. Clearly, the hand is not dissociated from the fisherman. When the contribution of these texts is removed from McKoon and Ratcliff's data, the effect of the associated/dissociated variable greatly decreases for the initial location and is slightly enhanced for the object (Glenberg & Mathew, 1992). Furthermore, Glenberg and Mathew replicated the McKoon and Ratcliff experiment using carefully constructed texts, and they found no effect of the associated/dissociated variable on the locations, but a substantial effect on the objects. In conclusion, support for the salience account appears to derive from an experimental artifact. When that artifact is removed, the salience account receives no support, and the mental model account continues to be supported.

Overall, the data are quite convincing that people construct spatial mental models while comprehending (in many circumstances), and that pictures facilitate the construction of such models. However, data from Glenberg and Kruley (1992) demonstrate that pictures can have additional facilitative effects. Those experiments (described in more detail below) were designed to uncover some of the ways in which pictures affect on-line processing of texts. In one experiment, subjects read texts alone, texts that were accompanied by a picture, and texts that were followed by a picture. Performance on a comprehension task was best when pictures accompanied the text. However, when pictures followed the texts (and thus were unlikely to have much of an influence on the representation of the information derived from the text) there was nonetheless a significant improvement in comprehension performance. These data point to an additional role for pictures, one that is consistent with the dual code theory. We are in the process of tracking down this additional role, but we have as yet little to report.

We have also made progress toward the second objective, identifying how pictures modify the processing of textual information. Our first efforts were directed at demonstrating that pictures may facilitate an important component process of comprehension, finding the antecedents of anaphors (Glenberg and Kruley, 1992). Subjects read texts requiring resolution of anaphors for which the antecedents were presented shortly before or well before presentation of the anaphor. We know from other research that increasing the time between the antecedent and the anaphor slows down and complicates anaphor resolution. An orthogonal manipulation was that the texts were accompanied by pictures or not. We thought that pictures might facilitate anaphor resolution because the anaphors that we used were terms describing the spatial locations of parts of objects (e.g., "the part on the top"). Thus, when anaphor resolution was difficult (when the antecedent was presented well before the anaphor), we expected the picture to have a substantial benefit. Rather than having to search through a mnemonic representation of the text for an appropriate antecedent, the reader could simply refer to the mentioned spatial location in the picture. However, when anaphor resolution was easy (when the antecedent was presented shortly before the anaphor) we expected little benefit of the picture. In this case, the required antecedent should be highly available in memory. The results across several experiments were very consistent. Antecedent distance affected processing and pictures affected processing, but contrary to our expectations, the two did not interact. Thus, pictures do not seem to enhance difficult anaphor resolution.

We believe that pictures help people to derive mental models (Glenberg & Langston, 1992), and we believe that these mental models are constructed using the visual/spatial sketchpad (Baddeley, 1992) of working memory (the details of this proposal are discussed in reference to Langston and Glenberg, in preparation, and Glenberg, Kruley, and Langston, in press, both of which are described later). Glenberg, Kruley, and Sciana (in preparation) pinpointed the use of the visual/spatial sketchpad in comprehension of text accompanied by pictures. Those experiments used the dual-task methodology championed by Baddeley to uncover those aspects of working memory utilized by a particular task. Suppose that comprehension of texts with pictures does require the sketchpad. In that case, concurrently performed tasks which also require the sketchpad will be performed less well. To test this prediction, we developed a task that we believe taps the sketchpad, a short term dot memory task. Subjects in the experimental version of the task were briefly shown an array of five dots in a grid (usually 7 X 7). At a later time, a test array was shown, and subjects determined if the test grid matched the study array. We also developed a control condition that required similar perceptual and response processes, but had no memory requirement. In the control condition, the study array was an empty grid. When the test array was shown, the subject responded as to whether a majority of the dots were above the center line of the grid.

In Experiments 1 and 2, the subjects comprehended texts presented with or without pictures. Each text was divided into eight segments, each segment consisting of one or more sentences. Each text segment was preceded by a study array and followed by a test array. We expected text comprehension to be facilitated by the pictures (and it was), and we expected comprehension to suffer when the experimental version of the dot task was used (and it did). More importantly was whether or not performance on the experimental version of the concurrent task was selectively disrupted when subjects comprehended texts presented with pictures. In fact we found this selective disruption. Although small numerically (about a five percent reduction) it was easily statistically significant in two experiments.

These results are suggestive of the use of the sketchpad for comprehension of texts with pictures. However, an alternative explanation for the findings is that presentation of pictures (which occurred in the interval between the study and test arrays) simply disrupted memory of the study array by distraction, perceptual processing, or interference with a long-term code. To demonstrate that the disruption only occurs during comprehension, in Experiment 3 we replicated Experiments 1 and 2, but removed the requirement to comprehend the texts. Thus, although the pictures and texts were presented, the subjects were instructed that they would never be tested on the texts. Several weeks after participating in the experiment, subjects were invited back to the laboratory to take a recognition test for the pictures.

The primary finding from Experiment 3 was that the experimental version of the concurrent task was not disrupted by presentation of the texts with pictures. That is, the disruption only occurs when there is a requirement to comprehend the texts, as in Experiments 1 and 2. This null effect is unlikely to be the result of low power. In fact, the experiment had a power of .99 to detect the smallest disruption found in the initial experiments. Also, the absence of disruption was not due to subjects blocking the pictures (e.g., by looking away). Recognition memory for the pictures was quite good.

One final piece of data is required to be confident that these results reflect use of the sketchpad when comprehending texts with pictures. We must demonstrate that the selective disruption does not occur when the concurrent task is not tapping the sketchpad. To do this, for Experiment 4 we designed two version of a concurrent task that should tap the articulatory loop component of working memory, but not the sketchpad. In the experimental version of the task, subjects studied a sub-span sequence of digits. At the test, the subjects were presented with two digits from the sequence and responded as to whether the digits were in the same order as in the studied sequence. The control version of the task did not require memory. Instead, at the test, subjects responded as to whether the two digits formed an odd or even number. As in the previous experiments, the segments of each text were embedded between a study and test sequence, and half of the texts were accompanied by pictures.

Once again, we expected pictures to facilitate comprehension (and they did), and we expected comprehension to suffer in the experimental version of the digit task (and it did). The critical question is whether or not performance in the digit task is selectively disrupted by comprehending texts with pictures. We did not find this selective disruption. Thus, when the concurrent task taps the sketchpad, performance on the task is disrupted

by comprehending texts with pictures (Experiments 1 and 2). When the concurrent task does not tap the sketchpad, performance on the task is not disrupted by comprehending texts with pictures (Experiment 4). Thus, the data point consistently to this conclusion: Comprehension of texts with pictures requires the visual/spatial sketchpad of working memory.

How is the sketchpad being used during comprehension? We believe that subjects are using it to build spatial mental models. Experiments reported in Langston and Glenberg (in preparation) support the claim that the models are spatial not only in what they represent, but also in the nature of the representation. Furthermore, these experiments demonstrate a functional characteristic of spatial mental models that we call noticing. Noticing is a process by which a reader can infer (from the spatial model) a relation that is not presented in the text. We believe that there are several preconditions for noticing. First, comprehenders must be building a spatial mental model. That is, they must be using a spatial dimension of the sketchpad to represent a text-relevant dimension (e.g., temporal order of steps in a procedure). Second, attention must be focused on at least one entity (representation of an object) in the model. Third, when the focused entity is juxtaposed with another entity, the comprehender notices the spatial relation between the entities and encodes this as an inference along the text-relevant dimension.

Noticing has several characteristics that recommend it as a procedure for generating inferences. First, the inferential process is constrained in several ways, thus preventing an inferential explosion. One constraint is due to the limited capacity of the sketchpad. Another constraint is that noticing only occurs amongst attended entities. Second, noticing results in a more complete or elaborated understanding of the text than that that could be derived from the text alone.

In the Langston and Glenberg (in preparation) experiments, subjects read texts describing a spatial layout. An example is given in Table 1. The layout is illustrated in Figure 1. Note that the last sentence of the text can be presented in either of two forms. In one form, the last object (eggs) is described in a location that, if an accurate spatial representation is being created, will be adjacent to the location of the first object (flour). We call this the notice position, because subjects should be able to notice the relation between the first and last objects. Alternatively, the last sentence of the text can describe the location of the last object that happens to be distant from the first object. We call this the not notice position. After the last sentence is presented, we probe for availability of the first object (flour) using a speeded recognition test. If subjects are creating accurate spatial models and noticing when the last object is in the notice position, then availability of the target (the first object) should be greater (and responding faster) than when the last object is in the not notice position.

We manipulated two additional variables to help pinpoint the nature of the putative noticing process. First, we manipulated the number of objects described before testing the availability of the target. Table 1 and Figure 1 illustrate the six-item condition. We also used a four-item condition. Our account of noticing is that it occurs in the limited capacity sketchpad of working memory. Given the capacity constraints, noticing may not occur in the six item condition because the target may have been lost from the model before the sixth item is presented. Second, we manipulated whether or not the text was accompanied by pictures. When pictures were presented, only the first three items accompanied the texts. Thus any noticing required construction of a spatial model, not just examination of the picture. If pictures help readers to build and maintain spatial mental models, we might expect noticing to occur for both the four and six item texts when they are accompanied by pictures.

The data are in Figure 2. The noticing effect is revealed by the slope from left to right, that is, faster responding when the last item is in the notice position than when it is in the not notice position. When pictures accompany the texts (upper panel), the noticing effect is found for both the six-item texts and the four-item texts. Now turn to the lower panel, which illustrates the results when pictures did not accompany the texts. Now, a noticing effect is found for the four-item texts, but not for the six-item texts. Apparently, the six-item texts (when presented without a picture) overload the capacity of the sketchpad.

These data are important for two reasons. First, they illustrate the noticing processes. Second, the data point to the nature of the representation of mental models. Remember that a mental model is a representation of what the text is about, not a representation of the text. A priori, a mental model may have many formats, e.g., propositional, spatial, distributed. The noticing data, however, point to a truly spatial, analogical representation. Given a propositional representation, for example, there is no reason to suspect any difference in availability of the

Table 1
Example of a text used in Langston and Glenberg (in preparation)

Mary was arranging ingredients on the counter to bake a cake.
Mary put the flour down first.
Then she put the sugar to the right of the flour.
Then she put the cocoa to the right of the sugar.
Next Mary put the baking soda in front of the cocoa.
Then she put the milk to the left of the baking soda.
Finally she put the eggs (to the left of) (in front of) the milk.

Note: The target object is flour, and it is probed after the last sentence. The eggs are in the notice position when described as to the left of the milk. The eggs are in the not notice position when described in front of the milk.

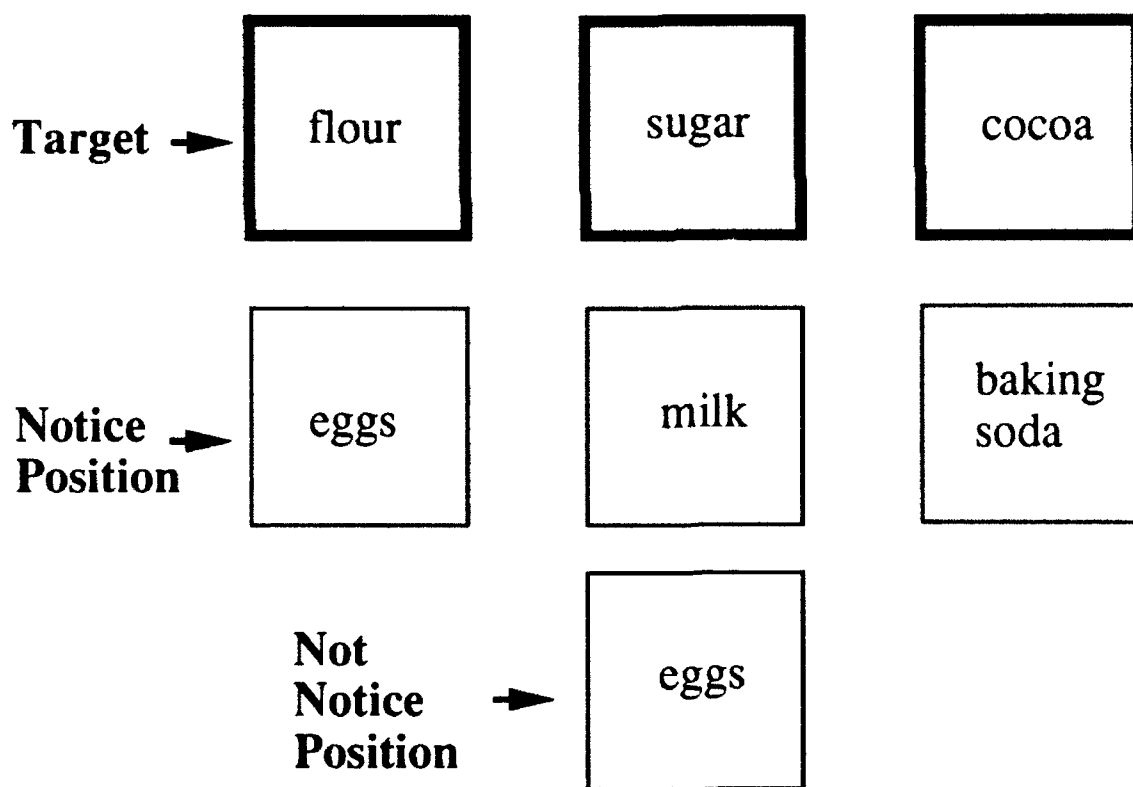
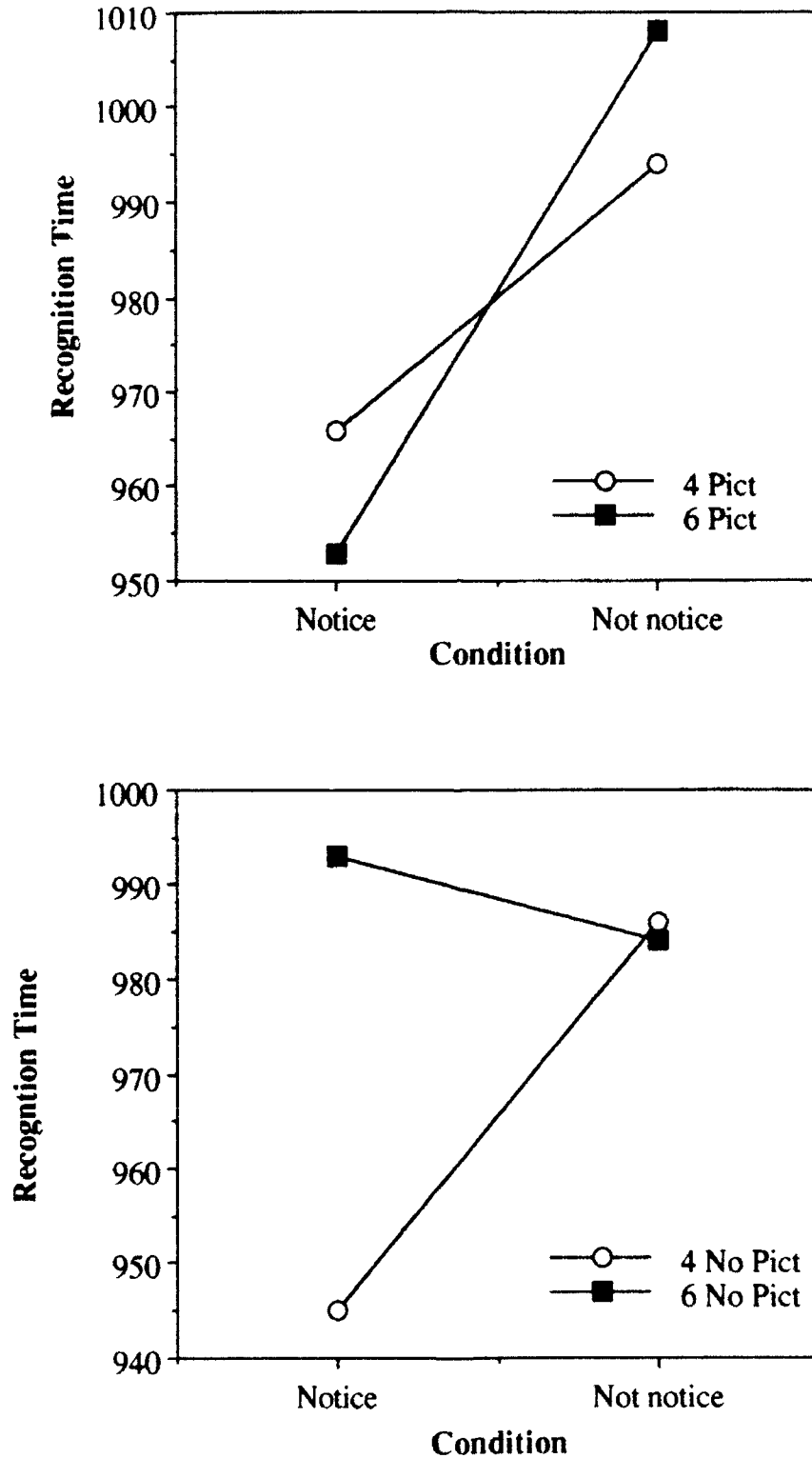


Figure 1: spatial layout corresponding to the text in Table 1. The boxes in bold correspond to items illustrated (in the six-item condition) when a picture accompanied the text.

Figure 2
Data from Langston & Glenberg (in preparation)



target as a function of the described position of the last item. Certainly a comprehender could apply a series of tests to the propositions to derive the fact that in the notice condition the last item is near the target. However, it is difficult to understand why a comprehender would ever bother to do so. If the representation of the mental model is created in a spatial analog medium, however, then the noticing effect is predicted. That is, given a spatial representation system and proper interpretation of the sentences, the last item must be adjacent to the first item in the notice condition. That is, because of intrinsic constraints on the spatial medium, the last item and the target item must be proximal.

The experimental research has led us to a series of conclusions about the construction and use of mental models and pictures during comprehension. The various conclusions, however, derive from separate experiments using a variety of texts, pictures, and methodologies. To what extent can we be sure that all of the processes and mechanisms can work together in a single coherent system? To answer this question, we set about to build a computer simulation of the construction of mental models. The simulation is far from being finished, but a preliminary report is given in Glenberg, Kruley, and Langston (in press). What follows is abstracted from that report.

In outline, the simulation constructs propositions from (highly-coded) words in sentences. These propositions are used to construct mental models and to direct the manipulation of the models. If a picture is available, it is used to guide the construction of the model. Once constructed, the model becomes a source of new information about the situation.

Nodes, propositions, and the mental model

One component of the simulation's memory is the node. We use nodes to represent specific objects (or more generally, entities), as opposed to classes, and each object described by a text has a corresponding node. The node encodes a limited amount of information about the object including its count (singular or plural), animacy (animate or inanimate), gender (male, female, or neuter), and semantic class. Because the simulation does not have a permanent knowledge base, this information must be hand-coded into the "text" that the simulation processes.

Five types of propositions are derived from the text. Word propositions encode verbatim the actual word(s) used to name an object. The proposition consists of the words used, and a pointer to the node named by the words. Language propositions encode some linguistic and semantic attributes such as whether the word is the grammatical subject and the given/new status, and they also include a pointer to the node. Although these propositions are necessary to the operation of the model, we will have little to say about them here. Description propositions encode unary attributes of objects such as size or color, and they also include a pointer to the node being described. Existence propositions encode the fact that an object exists. Finally, relational propositions encode relations among objects. The proposition includes a specification of the relation (e.g., "attached") and pointers to the nodes taking part in the relation. One of the pointers is designated as the "focus" of the proposition. The focus node is typically the grammatical subject (determined from the language proposition).

Each of these types of propositions can be activated by various sources (described shortly). Because activation of propositions is continuous and graded, there is little distinction between information "in" working memory and information "in" long-term store. Propositions that are highly activated are easy to retrieve, whereas propositions that have little activation are difficult to retrieve. Propositions are never deleted from memory, however. Nodes are not directly activated. Instead, the activation (availability) of a node is given by the activation of all of the propositions that point to that node. Thus, nodes, like propositions, are available to a graded degree.

We conceptualize the mental model as being constructed in a three-dimensional spatial medium corresponding to the visual/spatial sketchpad of working memory (Baddeley, 1990). The mental model is extremely limited in capacity because of limitations on activation. Entities in the model are pointers to nodes. Distance between pointers is representationally meaningful. That is, pointers that are closer together are more strongly related. The spatial dimensions ordinarily correspond to up/down, front/back, and left/right. However, when the simulation is assumed to have the requisite knowledge, the spatial dimensions may be used to represent

other, text-relevant dimensions such as time, energy, mass, friendliness, etc. The pointers (entities in the model) can be activated to various degrees, and when a pointer's activation falls below a threshold, it is removed from the model. Thus, unlike propositions and nodes, pointers are temporary.

Processing in the simulation

Processing is controlled by a working memory with multiple (but relatively fixed) capacities used for different tasks. The articulatory capacity is used to activate word and language propositions. The spatial capacity is used to read a word, examine a picture, and maintain pointers in the mental model. The general capacity can be deployed to support any of the activities already mentioned, and it is used to activate relation and description propositions. In addition, general capacity is used to support cognitive activities such as retrieving information and manipulating the pointers in the mental model.

Each activity (e.g., representing a pointer in the mental model, retrieving a proposition) requires a particular amount and type of capacity. However, the capacities are strictly limited and are quickly allocated. When available capacity is insufficient for an activity, capacity is recovered from memory using a proportionality algorithm. Each element in memory (mental model pointer or proposition) gives up a part of the capacity assigned to it proportional to the total amount of that capacity being used. This algorithm produces negatively accelerated forgetting (decrease in retrievability) and an extremely interactive system.

Retrieval is based on a resonance metaphor, much like the Minerva II model (Hintzman, 1986). The same retrieval process is used during comprehension (e.g., in retrieving antecedents for anaphors) and in memory tasks. In outline, retrieval works by assembling one or more propositions to use as retrieval cues. Next, activation is recovered proportional to the number of propositions used as cues. The cues are compared to all propositions in memory, and the activation of those propositions is increased in *direct proportion to their current activation (recency)*, in *direct proportion to their similarity to the cue (encoding specificity)*, and in *inverse proportion to the number of propositions contacted by the cue (cue overload, or fan effects)*. The result of a retrieval operation is a redistribution of (the previously recovered) activation across the propositions and a consequent change in the availability of the nodes pointed to by the propositions.

Whenever a relation or existence proposition is constructed, the simulation treats the proposition as a direction to update the mental model. This updating involves several major steps. First, activation is recovered to drive the following steps. Then, appropriate pointers are inserted into the model, if they are not there already. Next, if the proposition describes a relation between pointers that is not extant in the model, the pointers are moved into that relation. If a picture of the situation is available, that picture is used to help construct the model. For example, the text might describe Object A as near to Object B. Given a picture, the mental model would be able to represent whether Object A is to the left or right of Object B.

Finally, the simulation learns from the mental model using a process we call noticing. After the mental model is manipulated, the simulation searches for all pointers within the "noticing radius" of the pointer that was manipulated. If such a pointer is found, the simulation notices, that is, generates a proposition describing the relation between the manipulated pointer and the found pointer. These noticed propositions are supported by general capacity and stored in memory with pointers to the relevant object nodes. Prototypically, the noticed relation is spatial (e.g., "left of"), but the interpretation of the relation depends on the domain-relevant dimension assigned to the spatial dimension. By virtue of noticing, the simulation infers information that is not explicit in the text and learns from manipulation of its own mental model.

Reading a simple, one proposition SVO sentence proceeds as follows. (Each step requires that a sufficient amount of capacity be available or be recovered. Discussion of this is suppressed for clarity.) First, the subject noun is read and represented verbatim using articulatory capacity. If the word is marked as "new," a new node is generated to represent the specific object. If the word is marked as "given," a search of memory is conducted for a possible referent; if none is found, a new node is generated. The search (using general capacity) uses the retrieval algorithm, and the cues consist of information available about the word (e.g., gender). When the verb is read, it is encoded as a relation of a proposition, and memory is searched (using the retrieval algorithm) for an

appropriate initial argument (e.g., one that agrees in number with the verb). When the object noun is read, it is represented verbatim, and a node is retrieved or created for it. Then, the developing relation proposition is retrieved and completed.

When the completed proposition specifies a relation represented by one of the dimensions in the mental model, the proposition is treated as an instruction to update the model (using spatial capacity). First, however, if a picture is available, the picture is searched for the arguments of the proposition. If the arguments are found in the picture, then the spatial layout of the picture controls where the pointers to the objects are placed in the mental model.

Once the mental model has been updated, noticing occurs within the noticing radius of the pointer corresponding to the focus of the proposition. Any noticed relations are encoded propositionally, and stored with the appropriate nodes.

Because the simulation respects work on memory, it can successfully simulate standard findings such as recency effects and long-term recency effects (Glenberg, Bradley, Kraus, & Renzaglia, 1983) due to changes in capacities devoted to various propositions; proactive interference and release from proactive interference due to cue overload (Watkins & Watkins, 1975), as well as some rather unusual new findings such as the revelation effect (Watkins & Peynircioglu, 1990). Also, the simulation has had success in simulating work on mental models (Glenberg, et al., 1987), effects of pictures on comprehension (Glenberg & Langston, in press), map-learning (McNamara, Halpin, & Hardy, in press), as well as retrieval of antecedents for anaphors (O'Brien, Plewes, & Albrecht, 1990).

Simulation and data

To provide a sense of how the simulation works, we will describe in more detail how it deals with two phenomena, effects of mental models on foregrounding (Glenberg, et al., 1987), and learning of cognitive maps (McNamara, et al., in press). The simulation of Glenberg et al. (1987) illustrates how mental models are constructed from texts and how the model can influence comprehension processes. The simulation of the McNamara et al. results illustrates how pictorial information can be used to help construct mental models, and it illustrates the operation of the "noticing" process.

The point of the Glenberg et al. (1987) experiment was to demonstrate that the structure of the situation (as opposed to the structure of the text) plays an important role in foregrounding. When we say that a concept is foregrounded, we mean that the concept is readily available and thus easy to refer to, especially by a pronoun. To demonstrate that the structure of the situation influences foregrounding, Glenberg et al. (1987) showed that a critical object (e.g., sweatshirt) that is spatially associated with a main actor tends to remain foregrounded longer than a critical object that is spatially dissociated with the main actor. Figure 3 shows a comparison of the Glenberg et al. (1987) results and the results from the simulation. The dependent variable for the simulation is a transformation of the activation of the critical object node so that it can be more easily compared to reaction time.

The text used in the simulation is given in Table 2. It is a simplified version of the text used in Glenberg et al. (1987). Figure 4 portrays the situation in the simulation's memory immediately after reading the associated sentence. We will first describe how the simulation got into the state illustrated in Figure 4, and then we will describe differences between the associated and dissociated conditions from that point on.

Upon starting a new sentence, the simulation captures enough activation to process a typical, simple sentence, namely the activation needed to encode a subject, an object, and a relation. The simulation then reads the word "John" hand-coded along a number of dimensions: number (singular), animacy (animate), gender (male), given-new (given--unless concepts are specifically marked as new [e. g., by use of an indefinite article], they are treated as given), and grammatical class (subject). In addition, a semantic code is assigned to John that represents categorical information. These arbitrary semantic codes provide a way of assigning entities either to the same or to different categories. Because of the semantic code, the simulation does not confuse "John" with "Fido," which would otherwise be coded identically.

Figure 3. The data on the left are from Glenberg et al. (1987). On the right are data from the simulation of that experiment as described in the text.

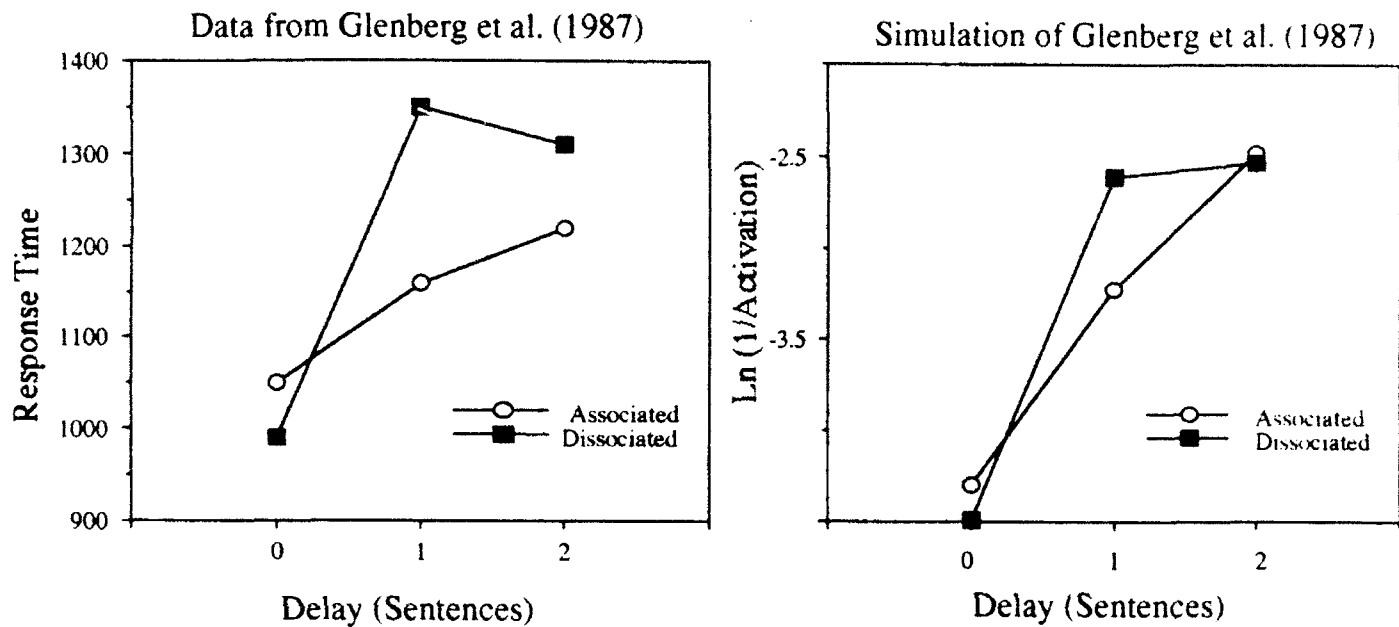
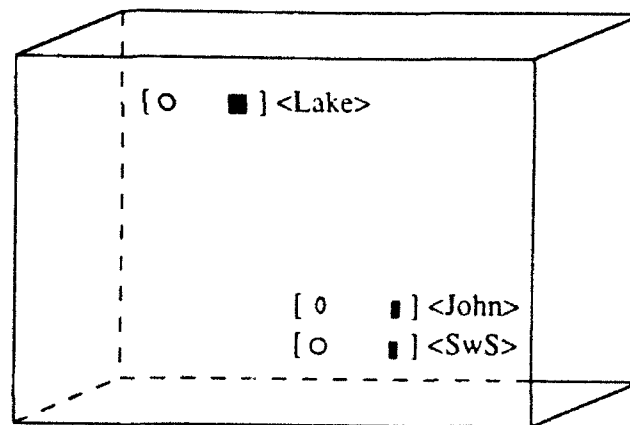


Table 2
Text used in the simulation of Glenberg, Meyer and Lindem (1987)
corresponding to the associated and filler sentences in Table 1

Critical (associated)	John put on a white sweatshirt.
Filler	John ran to the lake.
Filler	John has muscles.

Figure 4. Relevant aspects of the simulation after it has processed the associated sentence in Table 3. The top portion illustrates two dimensions of the three-dimensional mental model. Symbols in angle brackets are pointers to object nodes. The labels P1, P2, etc. refer to propositions derived from the text. The widths of the symbols within the square brackets correspond to the amount of spatial (ellipses), general (open rectangles) and articulatory (filled rectangles) capacity devoted to each proposition and to each pointer in the mental model.

Mental Model



• John

P1[[]] Word: <John>, "John"

P2[[]] Rel: <John>, attached to, <SwS>

P5[[]] Word: <John>, "John"

P6[[]] Rel: <John>, runs to, <Lake>

• SwS

P3[[]] Word: <SwS> "White sweatshirt"

P4[[]] Description: <SwS>, White

• Lake

P7[[]] Word: <Lake>, "Lake"

The simulation uses the coded information about "John" to search memory for any nodes to which the word "John" may refer. Because this is the first word of the text, none is found, and so a new node is created. The node includes the information that John is singular, animate, male, and the semantic code. A proposition (P1, in Figure 4) is formed that indicates that the word "John" was used to refer to this node, and the first argument in the proposition is a pointer to the node John (<John>). This proposition is supported with both articulatory and general activation from the amount reserved at the beginning of the sentence.

The simulation then reads "puts on." This is coded as the relation "attached to," along with the information that a singular active subject is required for this relation. A relation proposition is created (P2), but at this time only the relation "attached to" is specified. The arguments of the proposition must be either retrieved or read. The simulation uses the conditions "singular" and "active" to attempt to retrieve nodes that match the conditions specified by the coding of "puts on." The node John will be found (if there has not been interfering activity such as a long phrase in between the reading of "John" and "puts on"). The retrieval process boosts the activation of the word proposition (P1) and thereby the node corresponding to John. A pointer to the node becomes the focus of proposition P2, and this proposition is supported by general activation from that reserved at the beginning of the sentence. General activation is used, rather than articulatory activation, because the proposition does not correspond directly to anything that can be articulated in an articulatory loop. Note that the proposition is not yet completed because what John is attached to has not yet been read. The incomplete proposition is given an extra boost of activation so that it is not inadvertently lost before the proposition can be completed.

The simulation then reads "a white sweatshirt." Sweatshirt is coded as singular, new, inanimate, neuter, grammatical object, and given a semantic code. Because sweatshirt is coded as "new" (based on the indefinite "a") no search is conducted for a matching node. Instead, the Sws node is created. The fact that the words "white sweatshirt" were used to refer to the node is encoded by a word proposition, P3. In addition, descriptive information about this node, in particular that the object is white, is encoded by a description proposition (P4). Both of these propositions are supported by the activation reserved at the beginning of the sentence.

Because sweatshirt was coded as a grammatical object, the simulation searches for an incomplete relation proposition, and finds P2. A pointer to Sws is inserted into P2, and any extra activation used to keep P2 from being forgotten (before it was completed) is reduced.

After a relation proposition is completed, the simulation determines if that proposition has any implications for the situation (mental model) that is being represented. In this case, pointers to the John and Sws nodes are introduced into the mental model in close proximity. These pointers are supported by a combination of spatial and general activation.

Suppose that the test probe "sweatshirt" is presented at this time. Responding to this probe will be quick and accurate because the Sws node is highly activated. Note that this is the case in both the associated and the dissociated conditions (see below) because information about the sweatshirt has just been encoded in both cases.

Before the next sentence is attempted, the simulation again reserves activation. Because total activation in the system is limited, this reduces or "suppresses" information from the previous sentence. Upon reading the coded version of John, a search is initiated and the John node is found. A new proposition, encoding the fact that the specific word "John" was used again, is encoded (P5). This search process will have increased the activation of P1 (because the retrieval cue matches the proposition) and decreased the activation of other propositions, such as P3. The words "ran to" are encoded as the relation "moves to," and the incomplete proposition (P6) is supported by extra activation, until it is completed.

Because "the lake" is coded as "given" (based on the use of the definite article) a search for a compatible node is initiated. When none is found, a new node is created, and the proposition encoding the word "lake" is formed (P7). Because lake is coded as a grammatical object, the simulation attempts to retrieve an incomplete proposition (P6). When P6 is retrieved, a pointer to the lake node is added to it. All of this processing has greatly reduced the activation of propositions pointing to the Sws node.

At this point, some interesting processing occurs. With the completion of the proposition, the mental model is updated. A pointer to the lake node is entered into the mental model, and the simulation attempts to manipulate the mental model to be consistent with the recently encoded proposition, that John moves to the lake. In preparing to move the pointer representing John, the simulation notices that a pointer to Sws is very near to John. Should that pointer be moved too? The mental model does not represent (directly) the fact that John and Sws are attached, only that they are spatially close. The information that John is attached to his sweatshirt is given only in the propositions. Thus, the simulation attempts to retrieve information relating John and Sws by using as a retrieval cue a proposition consisting of a pointer to John, a pointer to Sws, and the relation "attached to." If a corresponding proposition can be retrieved, then both pointers in the model will be moved to the lake. In fact, the simulation is successful in retrieving P2, and both pointers are moved. These processes increase activation of the Sws node in several ways. First, activation of the Sws node is enhanced because retrieval of P2 increases the activation of P2 (and hence the activation of the Sws node). Second, manipulating the pointer to Sws in the mental model enhances the pointer's activation (and hence the activation of the Sws node). If the test probe "sweatshirt" is presented at this time, responding will be relatively quick. That is, retrieval of the Sws node will be facile because it is highly activated.

When the dissociated condition sentences are processed, the situation is exactly the same as in Figure 4, except that the relation in P2 is coded as "next to" rather than "attached to." In this case, when the mental model is updated (after completing P6), the pointer to Sws is not moved, and it receives far less activation (because it is not manipulated in any way). Consequently, the Sws node is not highly activated and responding to the probe is slower than in the associated condition.

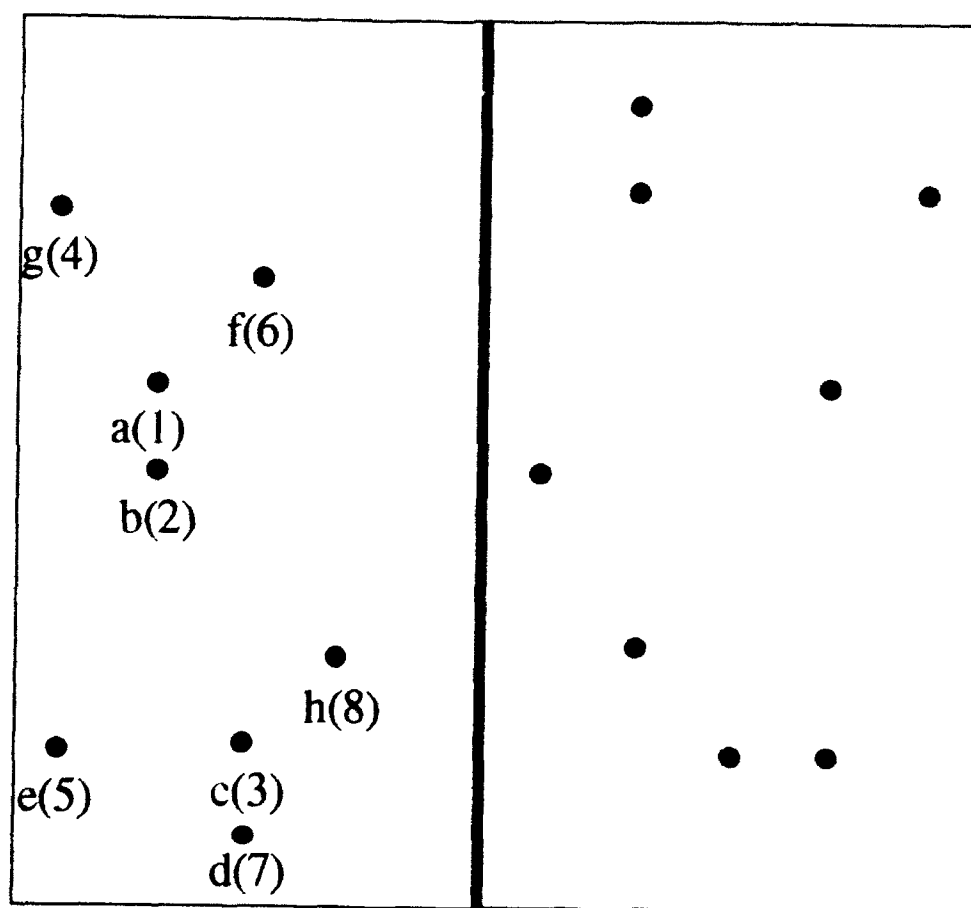
Why did we elect not to represent in the mental model the fact that John and sweatshirt are attached (in the associated condition)? First, we envision the mental model as extremely limited in capacity because it utilizes the limited visual-spatial scratchpad of working memory. Second, John could enter into many different types of relations with many different types of objects, and it is not clear how to determine which ones should be represented in the mental model. In the current version, the rule is simple: only include in the mental model the relations being represented by the spatial dimensions; all other relations are represented propositionally in memory. Third, our procedure has a natural consequence. If an object is not integral to the following text, the pointer to the object's node will soon be dropped from the mental model, as illustrated next.

The second sentence after the critical associated sentence is "John has muscles." On processing this sentence, the simulation adds a node for muscles, and introduces a pointer to muscles into the mental model. Propositions are formed encoding that John and his muscles are attached. Because sweatshirt is not referred to again, its activation is extremely low, and responding to a probe will be slow (see Figure 2). Furthermore, processing the mental model does not manipulate the pointer to Sws, its activation drops, and it is lost from the mental model (when its activation drops below a threshold, it is removed from the model). Thus, the model does not become cluttered with objects that could have been relevant, but soon turn out to be of little interest. Figure 2 illustrates both the data from Glenberg et al. (1987) and the results from our simulation using the text in Table 2.

Our second demonstration of the simulation addresses two issues. The first is how pictures help comprehenders to construct mental models. The second is how mental models can produce new learning based on "noticing" (Glenberg & Langston, 1992). We use results presented in McNamara et al. (in press) to demonstrate these features of the simulation.

The McNamara et al. paper examines the contribution of spatial and temporal contiguity to the development of spatial relations. The subjects were to learn the locations of objects on a map, much like that illustrated in Figure 5. Object locations are represented by dots, and the names of the objects (in the figure, not the experiment) are given by letters of the alphabet. In the experiment, the objects occurred in two regions, as indicated by the heavy line down the middle of the figure. After learning, subjects received several types of tests. In the region test, subjects had to quickly decide to which region a named object belonged. In the recognition test, the subject simply decided if an object name occurred. Because we have not yet implemented regions into our simulation of mental models, we will focus on the recognition test.

Figure 5. The picture used to accompany the simulation of the McNamara et al. (in press) data. The left-hand panel illustrates the object names (letters), the order in which the names were presented (digits), and their locations (dots). The right-hand panel illustrates the map-like stimulus actually available to the subjects.



In the experiment, subjects had continuous access to a map giving the locations of the objects, but not the object names, much like the right side of Figure 5. The names of the objects were given one at a time, by presenting an object name next to its location. A critical variable was the order in which the names were presented. The left side of Figure 5 uses lower case letters to represent object names and Arabic numerals to represent order of presentation of the names. Note that the right-hand side of the figure corresponds to what subjects saw most of the time; subjects never saw anything corresponding to the left-hand side of the figure.

Pairs of objects can be defined on the basis of whether the objects were temporally or spatially contiguous. Thus Objects a and b are both temporally and spatially contiguous, whereas Objects c and d are spatially contiguous, but not temporally contiguous. Objects e and f are temporally contiguous, but spatially distant, whereas Objects g and h are temporally and spatially distant. These pairs were then used as primes and targets on the object-name recognition test. For example, a prime, the name of Object a, would be presented, and the subject would respond "yes." Next, a target, the name of Object b, would be presented. The question of interest was how the spatial and temporal relations between the targets and the primes would affect speed of responding to the targets.

The response times to the targets (collapsed across the experiments reported by McNamara et al.) are given on the left-hand side of Figure 6. Note the interaction: responding to a target name is facilitated by a prime that was spatially and temporally close during acquisition, but not when the relation was just spatial or just temporal. Data from the simulation are presented on the right-hand side of Figure 6.

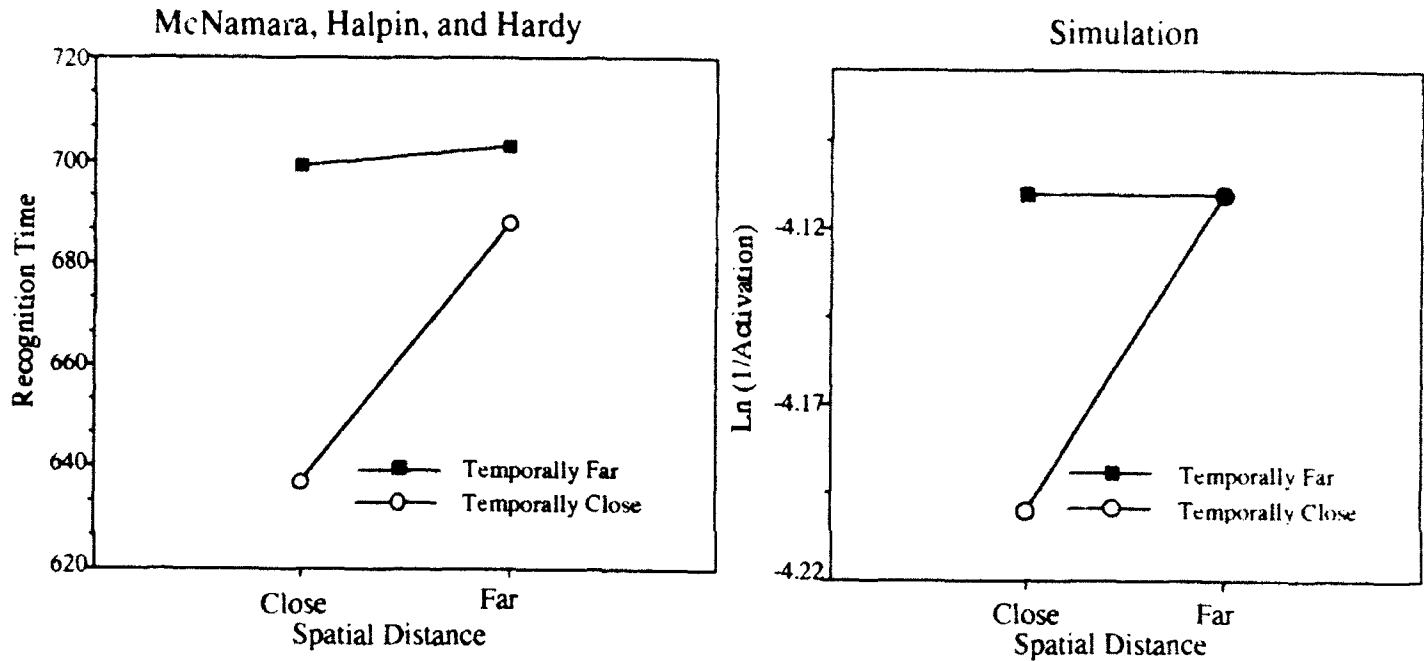
To simulate these data, we used a "picture" that provided metric information about the locations. When an object was mentioned, the simulation consulted the picture, scaled the location in the picture to the dimensions of the mental model, and entered into the mental model a pointer representing the object. Thus, the location of the pointer in the mental model was controlled by its location in the picture.

Whenever the mental model is manipulated (e.g., by entering a new pointer), the simulation engages in noticing. (Noticing also occurred in the simulation of the Glenberg et al, 1987 data, but discussion of it was suppressed for clarity). The idea of noticing is to use the structure of the mental model to encode relations that are not given explicitly in the text. To notice, the simulation examines spatial locations within the "noticing radius" (a free parameter in the simulation) of a manipulated pointer. If another pointer is within that radius, the simulation encodes the relation between the two pointers, and stores the proposition with pointers to the relevant nodes. Unlike other computational systems for generating inferences, this one is self-limited in three ways. First, noticing only occurs for objects represented in the limited capacity mental model. Second, noticing only occurs for objects within the noticing radius of manipulated pointers. Third, inferences are made only about the relations assigned (for the current text domain) to the spatial dimensions.

Consider how the simulation responds to the presentation of object names in the McNamara et al. experiment. When Object a is presented, a pointer is entered into the mental model, but there is nothing to notice. When a pointer to the node for Object b is entered into the mental model, the relation to Object a is noticed and stored. When the pointer to the node for Object c is entered into the model, no new relations are noticed, because the pointers to Objects a and b are outside the noticing radius of the pointer to Object c. The next (fourth) pointer entered into the model is the one to the node of Object g. With its entry, activation of the pointer to Object a is so low that it is dropped from the model. Similarly, by time the pointer to Object d is entered (seventh), the pointer for Object c has been dropped. Thus, although two objects may be spatially close in a picture, if their pointers are not concurrently resident in the mental model, no relation is noticed.

On the recognition test, responding to the name of an object requires retrieval of information about the object. That retrieval process activates various propositions, including propositions encoding noticed relations. For example, when the name of Object a (the prime) is presented, the proposition encoding its noticed relation to Object b is activated. This activated proposition partially activates the node for Object b (the target), producing facilitation when Object b is presented for recognition. On the other hand, responding to the name of Object c does not facilitate responding to the name of Object d, because no relation was noticed between these objects.

Figure 6. The data on the left are averages based on the experiments presented in McNamara et al. (in press). The data on the right are from the simulation described in the text.



Thus our simulation of the McNamara et al experiments demonstrates one way in which pictures can facilitate comprehension. In particular, a picture can provide metric information about objects to guide in the construction of mental models. Then, the mental model can be used to notice (encode) new relations, and thus learning more about the situation than is given by the text.

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- Langston, W. E., and Glenberg, A. M. (in preparation). Noticing in mental models: Evidence for analogical representations of text.
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C. Chronological list of publications

- Glenberg, A. M., & Langston, W. E. (1992). Comprehension of illustrated text: Pictures help to build mental models. *Journal of Memory and Language*, 31, 129-151.
- Glenberg, A. M., & Kruley, P. (1992). Pictures and anaphora: Evidence for independent processes. *Memory & Cognition*, 20, 461-471.
- Glenberg, A. M., & Mathew, S. (1992). When minimalism is not enough: Mental models in reading comprehension. *PSYCOLOQUY*.92.3.64.reading-inference-2.1.glenberg-mathews.
- Glenberg, A. M., & McDaniel, A. (1992). Mental models, pictures, and text: Integration of spatial and verbal information. *Memory & Cognition*, 20, 458-460.
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- Kruley, P., Sciama, S., and Glenberg, A.M. (in preparation). Comprehending texts with pictures uses the visual/spatial sketchpad.
- Langston, W. E., and Glenberg, A. M. (in preparation). Noticing in mental models: Evidence for analogical representations of text.

D. Professional personal associated with the research

Arthur Glenberg
Peter Kruley
William Langston
Sonia Sciama

E. Interactions

(i) Invited addresses

- Integration of pictures and discourse. Review of Air Force Sponsored Basic Research, November, 1989.
- Building mental models from text: A simulation of comprehension and memory. ARMADILLO-II conference, Texas A&M University, May 1991.
- Comprension del texto ilustrado: los dibujos ayudan a crear modelos mentales. University of Salamanca, July 1991.
- Building mental models from text: A simulation of comprehension and memory. Human Communiation Research Centre, University of Edinburgh, July 1991.

Building mental models from text: A simulation of comprehension and memory. Colloquium at University of Iowa, October 1991.

Comprehension of illustrated text: Pictures help to build mental models. In A. M. Glenberg & M. McDaniel (Co-chairs), *Mental models, pictures, and text: integration of spatial and verbal information*. Symposium conducted at the meeting of the Midwestern Psychological Association, May 1991.

Analogical processes in comprehension. University of Chicago, 1992.

Analogical processes in comprehension. Northwestern University, 1992.

Analogical processes in comprehension. Center for Interdisciplinary Studies, University of Bielefeld, Germany, 1993.

Invited colloquia on this research is scheduled at the following places between January and April, 1993.
Department of Linguistics, University of Bielefeld
Department of Psychology, University of Giessen
Department of Psychology, University of Leuven
Max Planck Institute, Nijmegen
German Association for Experimental Psychology

(ii) Consultative and advisory functions

July, 1991 Consulted with Dr. Angel Fernandez and his laboratory at the University of Salamanca, Spain for three days.

November, 1992 Consulted with Dr. Fernandez and Dr. Manuel Carreras (University of La Laguna) who visited Madison, Wisconsin for one week.